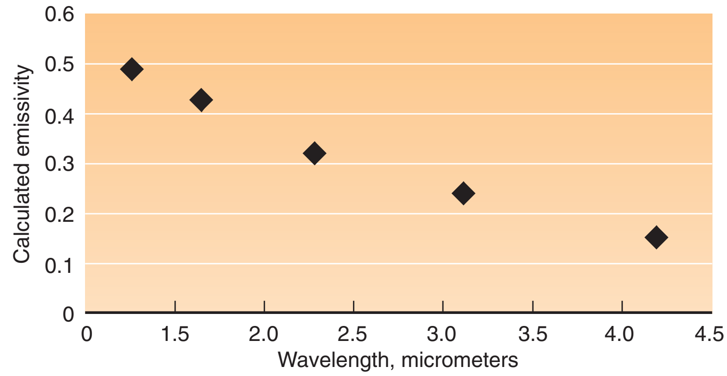
Measures for Measures



The emissivity of a surface as a function of wavelength must be determined to achieve highly precise surface temperature measurements.

DURING many physics-related experiments—especially those that involve the extreme pressures and temperatures of high-explosive detonations—scientists and engineers need to directly measure the temperature of a material's surface and, at the same time, its density or pressure. Investigators commonly use the infrared radiation emitted from a material's surface to infer its temperature. However, the accuracy of this approach is limited because the emitted radiation depends not only on a material's surface temperature but also on a property known as emissivity.

Emissivity is the ratio of the power radiated by a perfect emitter, called a blackbody, to the power radiated by the material in question. A blackbody is assigned an emissivity value of 1, and a material that does not radiate at all has an emissivity of 0. The values for all other materials fall between 0 and 1.

The emissivity of a radiating material depends on the type of material being studied, its surface conditions, and such properties as its roughness and color. A black surface radiates more than a shiny surface at the same temperature. Highly reflective materials have very low emissivities. For example, aluminum foil has an emissivity of about 0.03, one-thirtieth that of a blackbody.

Previous methods that use emissivity to determine temperature do not have the accuracy needed for many of today's applications. Rather than measure emissivity directly for each experiment, some researchers use data collected from past experiments in calculations that convert emitted power to temperature. However, this technique can result in errors ranging from 10 to 20 percent.

Livermore scientists need more accurate surface temperature measurements for their stockpile stewardship work. Such data help them better understand material properties at the microstructural level and how these properties change during a high-explosives shock. A highly accurate thermometry method for extreme temperatures will allow researchers to refine calculations of a material's equation of state.

Reducing the Error

To improve the accuracy of thermometry readings, Livermore physicists Peter Poulsen and Stanley Ault use the fact that emissivity and reflectivity must add up to one. The method they developed incorporates nearly simultaneous measurements of emitted and reflected radiation. With these measurements, they can compute the surface temperature and determine how emissivity varies with wavelength. For example, they can measure a metal's surface temperature with an error of less than 1 percent. "We developed this method to measure the temperature of shocked surfaces," says Poulsen. "Our readings are completed very quickly—in less than a millionth of a second."

Conventional infrared measurements do not take into account that emissivity is normally a function of the wavelength of the emitted radiation. "Characterizing the emissivity with a single number independent of the wavelength is not sufficient," says Poulsen. Most metals have an emissivity that decreases significantly with increasing wavelength, so that more emission takes place at shorter wavelengths. Scientists may, thus, interpret the observed radiation spectrum as resulting from a higher temperature.

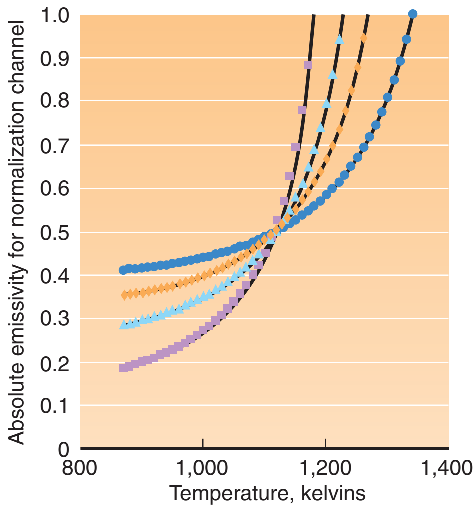
Putting Theory into Practice

The Livermore approach uses a multichannel spectrometer and an external light source to measure, almost simultaneously, the emitted and reflected powers over a range of wavelengths. The experimental apparatus developed by Poulsen and Ault to test the method incorporates a pulse-heated molybdenum foil. Car batteries provide the current for heating the foil. An inert gas replaces the air within the device to prevent oxidation of the foil. A window that is transparent to light in the infrared range of wavelengths provides optical access to the foil for the detectors that measure the emitted and reflected radiation.

In the experiments, batteries heat the metal foil until it reaches the desired temperature, as determined by a thermocouple connected to the foil's surface. Samples of the radiation (light) emitted by the heated foil pass through six fiber-optic cables and are recorded for 200 nanoseconds by the detectors of a multichannel spectrometer. An external pulse of full-spectrum light is then directed from the end of a fiber-optic cable to the metal's surface. The spectrometer's six detectors also record this reflected light and provide the results as the sum of emitted and reflected light. The entire process takes only a few hundred nanoseconds. Each channel measures the signal over a known range of wavelengths. The external light source is located at the same point in space as the detectors and illuminates the same area viewed by the detectors.

One detector serves as a reference channel, so that data and the governing relations from the remaining channels can be normalized to those from the reference channel. This process removes any dependency on the absolute magnitudes of the signals. Then for each nonreference channel, the normalized emitted-signal data are combined with the reflected-signal data to generate a curve that determines temperature as a function of assumed emissivity in the reference channel.

In an ideal experiment, the curves would intersect at one point, giving the temperature of the metal's surface as well as emissivity in the reference channel. However, because slight inaccuracies occur in setting up and performing experiments, the curves intersect at different points within a small area of deviation. Poulsen and Ault use this area of deviation to estimate the temperature and the uncertainty in the measurement. To validate their method, they compared the results obtained with the temperature recorded by the thermocouple. Poulsen notes, however, that the spectrum method can be used alone in applications that require noncontact measurement techniques.



The intersection of the four curves determines the measured temperature and its error. In this example, the temperature is 1,113 ± 1.8 kelvins. Emissivity in the reference channel is 0.490 ± 0.003. The thermocouple recording provided a temperature of 1,110.4 kelvins.

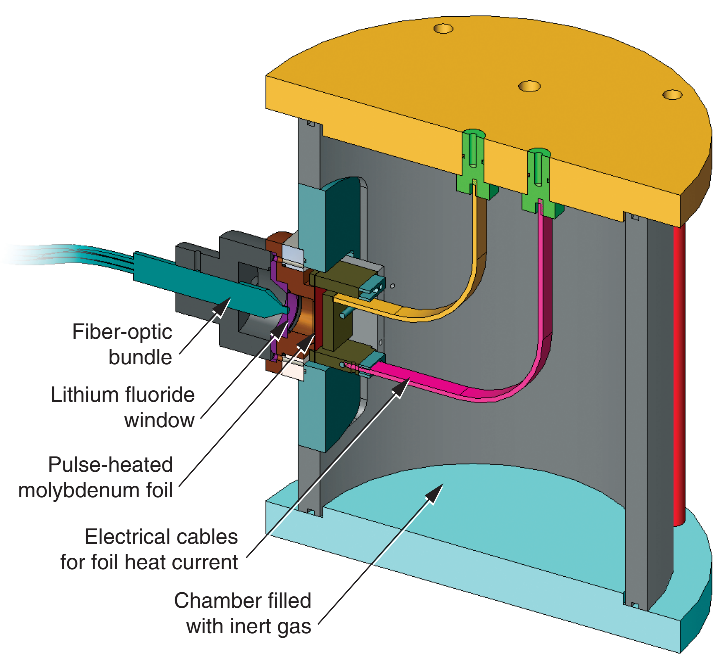
A Boon for Process Control

The accuracy of the spectrum method will allow Livermore physicists to acquire high-fidelity equation-of-state data on weapons materials undergoing high-explosives shocks. More applications abound in both research and industry. "This method will be beneficial in the field of process control," says Poulsen. "In the fabrication of steel, aluminum, plastics, or even silicon wafers, processes always depend on temperature." In fact, because materials can change phase as temperature changes, temperature often must be tracked dynamically during fabrication processes.

The ability to constantly monitor temperatures in jet-turbine engines is also of great interest to the aircraft industry. High-precision dynamic thermometry can help determine the optimum running temperature for jet engines. These high-performance engines run very hot—in fact, they are more efficient at higher temperatures. However, temperatures that are too extreme may cause safety and reliability problems. According to Poulsen, the spectrum method could be used to develop systems that constantly monitor and control the temperature of jet engines.

Because of its accuracy, the spectrum method can also be applied to determine when to replace parts. "Rather than routinely replacing parts when an average threshold for service has been reached, considerable resources could be saved by monitoring components and replacing them when their useful life is reaching the end," says Poulsen. "We developed this instrumentation for the Laboratory's shock experiments, but it can be useful across many fields, from defense to industry, because of its ability to improve safety and resource management."

—Maurina S. Sherman



To accurately determine the temperature on a metal's surface during a high-explosives shock, Livermore physicists developed an experimental device to measure the emitted and reflected radiation. Fiber-optic cables connected to detectors of a multichannel spectrometer record the data.

Key Words: emissivity, high-precision thermometry, infrared spectrometry, relative reflectivity method, spectrum method.

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